Wolfgang Burgholzer and Gerhard Bauer and Martin Posset and Werner Jammernegg

Analysing the impact of disruptions in intermodal transport networks: A micro simulation-based model

Analysing the impact of disruptions in intermodal transport networks: A micro simulation-based model

Abstract: Transport networks have to provide carriers with time-efficient alternative routes in case of disruptions. It is, therefore, essential for transport network planners and operators to identify sections within the network which, if broken, have a considerable negative impact on the networks performance. Research on transport network analysis provides lots of different approaches and models in order to identify such critical sections. Most of them, however, are only applicable to mono-modal transport networks and calculate indices which represent the criticality of sections by using aggregated data. The model presented, in contrast, focuses on the analysis of intermodal transport networks by using a traffic micro simulation. Based on available, real-life data, our approach models a transport network as well as its actual traffic participants and their individual decisions in case of a disruption. The resulting transport delay time due to a specific disruption helps to identify critical sections and critical networks, as a whole. Therefore, the results are a valuable decision support for transport network planners and operators in order to make the infrastructure less vulnerable, more attractive for carriers and thus more economically sustainable. In order to show the applicability of the model we analyse the Austrian intermodal transport network and show how critical sections can be evaluated by this approach.

Keywords: Intermodal transport network, network vulnerability, transport network analysis, traffic micro simulation, supply chain disruption

1 Introduction

The movement towards more and more global specialization and consequentially increasing international trade leads to a growing amount of global transport volume [16]. More transport volume, subsequently, also creates more and more competition between transport network providers as carriers search for more (cost) efficient, flexible and reliable transport flows [16,26]. The combination of different transport modes within a single transport chain offers opportunities to improve a transport system's performance [16], not just as an effective and reliable way of transport but also regarding the public aim for more environmentally friendly and sustainable transport flows [26]. Thus, combined transportation [14], and especially intermodal freight transportation, with its main leg of the transport being operated by rail, inland waterway or ocean-going vessel [8,20], is a frequently used alternative to mono-modal transportation [14,26].

Disruptions within a transport network, caused by natural disasters, technical problems, wear and tear or human malevolence are a major threat for a network's reliability and efficiency [19,30]. Therefore, it's a goal for transport network providers, in case of a disruption, to offer time efficient alternative routes to carriers.

Based on this need for efficient transport flows in case of a disruption, we develop a model which *analyses transport flows within intermodal transport networks when a disruption occurs* in order to identify the network's strengths, and more importantly, weaknesses [21,22]. We quantitatively measure a network's *vulnerability* which, based on [9,18,31], is the amount the performance level of a network drops when individual sections, further referred to as links, of the network are disrupted [22,30]. In particular, we measure the ability of a transport network to absorb the amount of transport which can not pass a disrupted link without considerable time delay in transportation. Thus, we identify links within a network which strongly degrade a network's performance. Such links are later referred to as *critical links* [32]. By considering terminals which allow a change of the transport mode, the model is perfectly useable for intermodal transport networks. Nevertheless, the model is also applicable to other network types.

Intermodal freight transport, which emerged as a research field in the last decade of the 20th century [1], is defined as a transport system which integrates at least two modes in a transport chain and where the handling units (mostly containers) do not change. The main leg of the transport thereby is operated by rail, inland waterway or ocean-going vessel, while the initial and final legs are operated by road [8,20]. The growing amount of global transport volume and the aim for more efficient, sustainable and environmental friendly transport flows have been the drivers for research on intermodal transport [16,26]. Nevertheless, research on intermodal transport network design or performance analysis is, while developing in recent years, still scarce [16,20].

Literature on the analysis of network-disruption similarly emerged since the 1990's [29,30]. Most of the research in this field concentrates on the development of models measuring a mono-modal transport network's vulnerability by means of indices [e.g.: 13,15,21,28,30,31]. These indices are based on mathematical models which depend on few input factors such as capacity utilisation, the importance of a network's links or the length of these links. The complexity of intermodal transport networks, however, with its plurality in transport modes and decision makers, makes it impossible for such mathematical models to reflect [2].

Thus, and motivated by more recent developments in the research fields of traffic assignment and traffic micro simulation [e.g.: 3,23,29,35] as well as research on agent-based approaches in the field of transport logistics [5], our model uses a *traffic micro simulation* as its core module. A traffic micro simulation makes it possible to analyse the entities of a network individually as well as with their dependencies and relationships to other entities [24,34]. Therefore, traffic micro simulation is more and more frequently used as the method of choice for solving and analysing traffic problems [35] as it dynamically and stochastically models each traffic participant and its movements within a transport network [7,23].

This paper is structured as follows. In Chapter 2 we present the model in detail, i.e. its data base, assumptions and detailed operations. Chapter 3 gives an overview of the used network performance indicators (NPI's) in order to measure the criticality of individual network links. Furthermore, Chapter

4 shows the application of the model to the Austrian intermodal transport network. The network itself as well as crucial findings are outlined. Chapter 5 concludes the paper by pointing out the advantages and limitations of the model as well as further advancement and research opportunities.

2 The simulation model

In this chapter the *traffic micro simulation model* is described. The goal of the model is to identify critical links within an intermodal transport network. For this purpose, one link at a time is analysed by looking at the influences a disruption has on the traffic participants which normally pass this link. Therefore, the model, firstly, reproduces the intermodal transport network as well as its actual traffic before, secondly, one of the network's links is disrupted. Then, a traffic micro simulation is used in order to navigate the traffic participants through the, now disrupted, network. The criticality, thereby, is primarily measured as the total delay of all traffic participants in the network due to the simulated disruption [32].

2.1 The intermodal transport network

The intermodal transport network is modelled by *links* and *nodes*. A link of the network, on one hand, is always located between two nodes. Nodes, on the other hand, are either crossings of the underlying network or terminals which make a mode change in a fixed handling unit possible and therefore are relevant for intermodal transport (container terminals). The traffic participants are called *transport units* in this paper. These transport units are the entities of the micro simulation.

Both, the network dimensions as well as the generation of the transport units are based on collectable data of the underlying networks. Above all, these data include, both for passenger and freight traffic, capacity, throughput, utilisation and physical dimensions of each link and node. Moreover, the average speed of every passenger and freight transport unit on a specific link is provided for the model. Upon these data, the actually occurring freight and passenger transport units are simulated. The transport units are generated onto traces which serve as possible time slots for passing a specific link. The traces are simulated according to the capacity of the specific links.

A disruption is described by its duration, its time of occurrence and the capacity reduction it induces. These three variables are referred to as *disruption parameters*. In case of a disruption, each transport unit, which normally would pass the now disrupted link, chooses between three different variants (as shown in Figure 1).

- Drive on a free trace through the disrupted link (after the end of the disruption or during the disruption when the reduction of the link's capacity is lower than 100 percent) (variant 1) or
- stay on the current transport mode and use a free trace on an alternative route (variant 2) or
- choose to switch the transport mode and continue on a free trace of the newly selected alternative route (variant 3).

INSERT FIGURE 1 HERE

Every transport unit will, in this juncture, decide itself for the variant and route with the *shortest transport time* [12].

2.2 The traffic micro simulation

The traffic micro simulation, which navigates the transport units through the network, is *event-driven* and *agent-based*. During the simulation, multiple events, like the assumed disruption at the beginning and later the decisions of each individual transport unit, occur. These events impact and trigger the flow of the program [10]. As these events, in turn, are often based on individual decisions of each individual transport unit, the programming approach can also be characterised as being multi-agent-based [4,11].

R was chosen as the programming language and environment. R is especially known for its use in statistical computing and graphics [27]. Its extensive data handling, preparation and analysis tools as well as its highly flexible, array based programming language were decisive factors for our implementation.

2.3 Model assumptions

The model (as described in detail in Chapter 2.4) is based on the following assumptions:

- Each transport unit acts rational. The rational goal is to *minimise the transport time*.
- Each transport unit always has complete information. Thus, each transport unit knows immediately when a disruption occurs about its disruption parameters. Each transport unit also has full knowledge of the chronologically upstream transport unit's decision as well as the utilisation of the terminals and the alternative routes. In this regard, transport unit A is chronologically upstream to transport unit B when it arrives earlier at the starting point of a possible route and therefore can decide earlier whether it wants to take this route or not.
- It is assumed that the number of arriving transport units per period is Poisson distributed [6].
- Regarding the decision which transport unit will be processed as the next one (see Chapter 2.4), freight and passenger transport units are handled the same way. In reality, however, especially at water gates and at train dispatching, passenger transport units often are ranked preferably over freight transport units. Nevertheless, we reward this fact, by differing the average speed, based on real-life data, by type of transport unit (freight or passenger transport unit), transport mode (rail, waterway or road) and day time (night or day). The average speed in this juncture includes delays due to the lower priority ranking of freight transport, like waiting times for free traces or at terminals and water gates.
- The underlying, average capacity utilisation data for the container terminals throughout the day is assumed to be constant while the capacity utilisation data for the links distinguishes between day (higher utilisation; higher percentage of passenger transport units) and night (lower utilisation, higher percentage of freight transport units).
- Passenger transport units do not utilise the existing container terminals. They, however, always (and not just at a node in the network) have the possibility to change to the transport mode road without utilising the terminals. They then go on by using replacement bus services.

- Generated transport units are able to turn around and drive back in the opposite direction. A considerable delay is attached to such an action.

2.4 Detailed operation of the model

This chapter describes the detailed operation of the model step by step by using the case of the railway link St. Pölten ⇆ Amstetten of the Austrian intermodal transport network as example. Figure 2 gives an overview about the nine steps of the detailed operation. The model analyses one link at a time by looking at the influences a disruption has on the transport units which normally pass this link.

INSERT FIGURE 2 HERE

Step 1: In a first step, the already defined, possible alternative routes of the links are uploaded into the model. Each link is, therefore, located within pre-defined monitoring limits. These limits can be interpreted as the farthest away from the disruption located, usable starting points for alternative routes within the considered network. Figure 3 shows this procedure for the link St. Pölten ⇆ Amstetten with the monitoring limits being Linz (in the west) and Wien (in the east). This means that the main flow of traffic is taking place between Wien and Linz and that these two nodes are the starting points of at least one alternative route which is the farthest away from the disruption. Figure 3 also shows the possible alternative routes for transport units in this case.

INSERT FIGURE 3 HERE

Step 2: The possible traces through the analysed link and through all possible alternative routes are generated. These traces are modelled according to the underlying capacity data by the network infrastructure provider for both directions of traffic flow. The link St. Pölten ⇆ Amstetten, is one of the highest capacitated sections of the Austrian intermodal transport network as it contains at a minimum two and mostly four tracks. It is, therefore, able to serve up to 399 trains per day [25]. Thus, 399 traces are simulated in a 24 hour window around the geographic midpoint of the link. The inter-arrival times of these traces are Poisson distributed and can be occupied by a transport unit.

Step 3: Now, the respective transport units, according to the obtained throughput data of freight and passenger transport units, are generated on these traces. As, in real-life, 317 trains go by the link St. Pölten ⇆ Amstetten (throughput) each day [25], 317 of the 399 traces are occupied by passenger and freight transport units (for this link: 150 freight transport units and 167 passenger transport units). 82 traces are not occupied. Figure 4 illustrates such a generation of transport units. Here, the passenger and freight transport units are generated on a straight line, which can be understood as an extension of the disturbed link.

INSERT FIGURE 4 HERE

Step 4: Furthermore, the model simulates a disruption with its three disruption parameters (see Chapter 2.1) in the geographic midpoint of the considered link. The simulation of a disruption with specific disruption parameters on a specific link is called a *scenario*. Therefore, the possible traces through the disrupted link are reduced according to the defined disruption parameters. The situation as it is now, with the alternative routes, the by transport units occupied and free traces and the disruption generated, can be referred to as "starting position" (see Figure 4).

Step 5: The time it (would) take each transport unit to get to the place of the disruption or to the starting point of each alternative route is calculated.

Step 6: Then, for every possible route (the way through the disrupted link or via the alternative routes) the transport unit which is the chronologically closest to each route is selected (see the arrows above selected transport units in Figure 4).

Step 7: The total time it requires each of these selected transport units to navigate to the targeted monitoring limit (Linz or Wien) is calculated. Therefore, any change-of-direction-, mode transition- and waiting time is considered. Similar to studies by Gawron [12] our decision method is handled iteratively. With each iteration, the transport unit with the lowest total time to the monitoring limit uses the corresponding trace on the selected route and is processed (see the star in Figure 4). This means that the selected transport unit chooses the route it minimises the transport time with.

Step 8: The selected transport unit and trace are then stored in the results matrix and not taken into account for following iterations.

Step 9: Steps 6 to 8 are repeated until the disruption does not affect the transport units any longer. If so, it is assumed that the normal service is restored and the disruption has no further effect on the traffic on this link.

In order to receive statistically meaningful and significant results each disruption is applied 100 times on every analysed link. All in all, the model delivers the following results for each affected transport unit and every analysed link:

- The route choice and the accordingly used terminal.
- The transport time without disruption.
- The transport time with disruption.
- The time delay due to the disruption.

3 Network performance indicators

The criticality of links is evaluated by network performance indicators (NPI's). We generate five NPI's out of the process mentioned in Chapter 2.4. These indicators can be divided into two categories. The indicators of the first category measure the impact of a disruption at a certain link for the *entire network* while the indicator of the second category measures the impact of a disruption on the *individual transport units*.

In general, an investigated link is more critical, either for the entire network or for the individual freight transport unit, the higher the values of the indicators are. High values in turn can be the result of heavy traffic via and a high utilisation of the considered link as well as insufficient alternative routes. By summarising over all links, these indicators can be calculated for the entire network as well. Thus, entire networks can be analysed and compared to each other.

3.1 Impact on the entire network

Total Disruption Delay Time One of the most important indicators in determining the criticality of a link is the time delay for all (freight) transport units if a disruption occurs [31]. Based on the purpose of this indicator, we refer to it as Total Disruption Delay Time (TDDT). It is the sum of the delay times of all affected freight transport units if a certain disruption occurs on a particular link.

Reach of Disruption Another set of important indicators refers to the reach of disruption. These indicators are the *number of affected transport units* as well as the *influence distance* and the *influence duration* of a disruption. The number of affected transport units reflects the number of transport units influenced in their normal route by the disruption. The influence distance in turn is the physical distance at the time of disruption between the place of impact and the affected transport unit which is, at the time of the disruption, the farthest away from the place of impact. Likewise, the influence duration is the temporal distance at the time of disruption between the place of impact and the affected transport unit which is, at the time of the disruption, the farthest away from the place of impact.

3.2 Impact on individual transport units

Average Disruption Delay Time The impact of a disruption on each individual transport unit is measured by the time delay of every (freight) transport unit. In order to compare different links, the average delay time for an affected transport unit when specific disruptions, and hence scenarios, occur is calculated. This indicator is referred to as Average Disruption Delay Time (ADDT). It provides information on the impact of a particular disruption, on a particular link, to the respective individual transport units.

4 Case study: The Austrian intermodal transport network

The model is applied to parts of the Austrian intermodal transport network, focusing on the rail and inland waterway network (as the main leg of transportation) as well as on container transport. Figure 5 shows the North Eastern area of this network in order to give an idea of the considered rail and inland waterway network. The Austrian road network is not part of the analysis. It, however, is used as a possible alternative mode choice in case of a disruption. Thus, the model analyses the effects on the network as well as the individual freight transport units if disruptions at specific links of the Austrian rail and inland waterway infrastructure network appear.

INSERT FIGURE 5 HERE

4.1 Underlying network

The analysed network represents the intermodal transport subnet of the Austrian transport network. The network includes the important rail, inland waterway and, as possible alternative routes, the road transport connections within Austria. Connections with neighbouring countries, if relevant for the Austrian intermodal transport, have also been included. Overall, the considered Austrian intermodal transport network consists of 110 links, thereof 78 being rail links, five being links on the inland waterways and 27 being road links. Overall 20 container terminals make the switch between the three considered modes possible.

The model is based on data from the high-level rail [25] and inland waterway network in Austria [33]. This data includes capacity, throughput and utilisation of each link and container terminal for passenger and freight traffic. Moreover, data of the actually driven average speed for each mode and link (particularly taking the considerable difference in the average speed of freight transport during the day and night into account) is available.

4.2 Considered disruptions

When applying the model to a network, the characteristics and size of the network have to be taken into account. In the case of the Austrian intermodal transport network, the relatively small size of the network slightly lessens the applicability of the model, as large-scale alternative routes are not available within the network. Therefore, the use of the model applies to the Austrian network of intermodal transport only for disruptions up to 24 hours of duration. When applying the model to larger networks, this restrictive assumption is not necessary.

The chosen durations and capacity reductions of the disruptions reflect, according to experts of the infrastructure providers, realistic incidents. Each water gate on the Austrian part of the Danube has two gate chambers and nearly each rail link consists of at least two rail tracks. Therefore, we assumed capacity reductions of either 50 or 100 percent. The duration of the disruption models short incidents. For example, it approximately takes two hours to remove a tree which might have fallen on rail tracks while maintenance jobs on a gate chamber often last about six hours and blockades of the Danube due to high water normally last between one and six days [33]. Table 1 presents the disruption parameters used for this specific network. As mentioned in Chapter 2.4, each disruption parameter subset can be referred to as scenario applied onto a link.

INSERT TABLE 1 HERE

As applying the model to every link of the network would have resulted in an unreasonably high effort, *relevant links* have been selected beforehand. According to experts of the respective infrastructure providers as well as based on the actual freight throughput [25,33] the number of further analysed links has been reduced to 19 relevant links (14 rail and five waterway links). Next, each of the 18 possible scenarios (as shown in Table 1), has been applied 100 times to each relevant link. This leads to 1,800 program runs per relevant link and, thus, results in 34,200 simulation runs in total.

4.3 Case study results and discussion

The analysis provides some very interesting results. Summarising over all scenarios of the relevant links, 16.84 percent of all transport units affected by a disruption choose an alternative route over the possibility of driving through the disrupted link. In particular, transport units originally going by ship often choose an alternative route (which in Austria, with the Danube as the only inland waterway relevant for intermodal transport, always results in a change of the transport mode) in order to minimise the transport time (64.32 percent of the time). Figure 6 shows the percentage of transport units choosing an alternative route in case of a disruption for every relevant link.

INSERT FIGURE 6 HERE

This indicates the main difference between the two analysed transport modes. Each transport unit's goal to minimise the transport time heavily favours faster transport modes. This results in *a preferred use of the rail and road networks in case of a disruption instead of the water network*. For all links of the inland water network the NPI's TDDT and ADDT support this assumption. Both indicators have negative values in any scenario. This means, that a faster average transport time can be achieved by the transport units, when a disruption occurs. The reason for that are the faster alternative routes which compare favourably to the route via the disrupted link. Despite heavy transition and waiting times at the terminals the transport units gain time by taking an alternative route. According to these results only links of the railroad network could be determined as critical.

Table 2 shows a comparison of the NPI's of each relevant rail link, averaged over all 18 scenarios (see Table 1 in Chapter 4.3). The rail links are sorted by decreasing TDDT.

INSERT TABLE 2 HERE

Considering the *TDDT*, the table especially points out the links *St. Valentin/Enns ⇆ Linz and Linz ⇆ Marchtrenk as relatively critical for the network*. Disruptions on these links, by far, cause the highest average TDDT of the network. Regarding the reach of disruption and its three NPI's (the number of affected transport units, the influence distance and the influence duration) these two links are also ranked in the top half of relative criticality. Deeper analysis shows that especially two factors are responsible for their relative criticality. Firstly, the relatively high utilisation and throughput even without a disruption and, secondly, the absence of short pathed alternative routes at the same mode. However, both links show relatively better results if disruptions with a shorter duration and less capacity reduction occur. The reason is that most transport units then take the route through the disturbed link as they are less dependent on the alternative routes. Exemplarily, Table 3 shows the average relative impact of different scenarios for the link St. Valentin/Enns ⇆ Linz. In this table the NPI for each scenario of this link is relatively compared to the maximum NPI of a relevant link (scaled with 1) and the minimum NPI of a relevant link (scaled with 0) in the respective scenario. You can see that the link St. Valentin/Enns ⇆ Linz is relatively less critical when disruptions with lower duration and capacity reduction occur.

INSERT TABLE 3 HERE

One very interesting case is the link *Wien ⇆ St. Pölten.* It is by far the most critical link according to the reach of disruption (see Table 2). Looking at the average TDDT, though, this link is relatively uncritical for the network. The main difference between this link and the two links mentioned above is that there are suitable wide-range alternative routes available for this link. As can be seen in Table 4, this results in relatively less time delay for the transport units when disruptions with long duration and high capacity reduction occur. For all other scenarios, however, the link Wien ⇆ St. Pölten is one of the relatively most critical.

INSERT TABLE 4 HERE

Focusing on the influences of disruptions on the individual transport units, the link Neumarkt ⇆ Passau is the relatively most critical (see Table 2). Again over all scenarios summarised, ADDT shows that each affected freight transport unit suffers the highest time delay at this link.

5 Conclusions

This paper describes the operation of an event-driven and agent-based traffic micro simulation model. The model simulates the actual traffic and analyses the impact of specific disruptions on the network. Thus, critical links for the network and the criticality of the whole network can be identified. This approach specifically takes transfer terminals into account. Therefore, the model is especially useful for the simulation of intermodal transport networks and, generally speaking, for combined transport.

The core principle of the model makes it possible to process the simulated transport units according to the sequence they arrive at the starting points of the alternative routes. Due to this fact, the route decision of every transport unit takes the decisions of the transport units chronologically upstream into account.

Based on the broad data base and the logical operations of the model, the transport time and route choice of each affected transport can be derived. This information is the basis for the calculation of NPI's and for further analysis. Especially the identification of critical links and their cause of criticality deliver substantial insights for the network providers. Based on these results, decisions for future developments of the network can be made.

It has to be mentioned, however, that the approach is more effective when analysing large transport networks. The larger the underlying network, the more large-scale alternative routes are available and the better the influences of disruptions with longer duration can be evaluated. Furthermore, it has to be noted that a decision based on the transport time alone might not be sufficient. Thus, an addition of the total transport costs (cp. [15]) to the transport time as decision parameter for each transport unit is intended. Such a Multi Criteria Decision Making Approach (cp. [17]) may result in different route decisions. Considering the case of the Austrian intermodal transport network, a decision based on transport costs in addition to the transport time would favour the waterway more as the transport mode of choice.

Acknowledgements

The authors would like to thank Hans Häuslmayer (h2 projekt.beratung KG) and Monika Weishäupl (WU Vienna University of Economics and Business, Department of Information Systems and Operations) for assisting with their expertise concerning intermodal transport networks in general and especially in Austria.

References

[1] Y.M. Bontekoning, C. Macharis, J.J. Trip, Is a new applied transportation research field emerging?—A review of intermodal rail–truck freight transport literature, Transp. Res. Part A: Policy and Pract., 38 (2004) 1-34.

[2] A. Caris, G.K. Janssens, C. Macharys, Modelling Complex Intermodal Freight Flows, in: M.A. Aziz-Alaoui, C. Bertelle (Eds.), Understanding complex systems, Springer, Berlin-Heidelberg, 2009, pp. 291-300.

[3] N. Cetin, A. Burri, K. Nagel, A large-scale agent-based traffic micro simulation based on queue model, in: Proc. of 3rd Swiss Transp. Res. Conf. (STRC), Monte Verità, Ascona, 2003.

[4] P. Davidsson, Multi agent based simulation: beyond social simulation, in: S. Moss, P. Davidsson (Eds.), Multi Agent Based Simulation, Springer, Boston, 2001, 141-155.

[5] P. Davidsson, L. Henesey, L. Ramstedt, J. Törnquist, F. Wernstedt, An analysis of agent-based approaches to transport logistics, Transp. Res. Part C: Emerg. Technol., 13 (2005) 255-271.

[6] D. Dolic, Statistik mit R: Einführung für Wirtschafts- und Sozialwissenschaftler, Oldenbourg, München, 2003.

[7] R. Dowling, J. Holland, A. Huang, Guidelines for applying traffic microsimulation modeling software, Dowling Associates, Oakland, 2002.

[8] European Conference of Ministers of Transport, Glossary for Transport Statistics, second ed., European Conference of Ministers of Transport, United Nations Economic Commission for Europe Statistical Division and European Union Eurostat, 1997.

[9] A. Erath, J. Birdsall, K.W. Axhausen, R. Hajdin, Vulnerability assessment of the Swiss road network, Trans. Res. Rec.: J. of the Transp. Res. Board, 2137 (2009) 118-126.

[10] J.R. Evans, D.L. Olson, Introduction to simulation and risk analysis, Prentice-Hall, Upper Saddle River, 1998.

[11] J. Ferber, Multi-agent systems. An introduction to distributed artificial intelligence, Addison-Wesley, Bonn, 1999.

[12] C. Gawron, Simulation-based traffic assignment: Computing user equilibria in large street networks, Inaugural-Dissertation, Mathematisch-Naturwissenschaftliche Fakultät der Universität zu Köln, Köln, 1998.

[13] S.P. Gorman, The vulnerability of networks and the resurrection of distance, in: S.P. Gorman (Eds.), Networks, security and complexity: The role of public policy in critical infrastructure protection, Edward Elgar, Cheltenham, 2005, pp. 50-76.

[14] M. Gronalt, L. Höfler, D. Humpl, A. Käfer, H. Peherstorfer, M. Posset, H. Pripfl, F. Starkl, Handbuch Intermodaler Verkehr – Kombinierter Verkehr: Schiene-Straße-Binnenwasserstraße, first ed., Bohmann, Wien, 2010.

[15] E. Jenelius, T. Petersen, L.G. Mattsson, Importance and exposure in road network vulnerability analysis, Transp. Res. Part A: Policy and Pract., 7 (2006) 537-560.

[16] J.W. Konings, H. Priemus, P. Nijkamp, The future of intermodal freight transport: operations, design and policy, Edward Elgar Publishing, Cheltenham-Northampton, 2008.

[17] G. Kou, Y. Shi, S. Wang, Multiple criteria decision making and decision support systems - Guest editor's introduction, Decis. Support Syst., 51 (2011) 247-249.

[18] V. Latora, M. Marchiori, Vulnerability and protection of infrastructure networks, Phys. Rev. E, 71 (2005) art. no. 015103.

[19] J.S. Lee, T.J. Kim, Spatio-Temporal models for network economic loss analysis under unscheduled events: A conceptual design, in: A.T. Murray, T.H. Grubesic (Eds.), Critical infrastructure – reliability and vulnerability, Springer, Berlin Heidelberg, 2007, pp. 57-80.

[20] C. Macharis, Y.M. Bontekoning, Opportunities for OR in intermodal freight transport research: A review, Eur. J. of Oper. Res. 153 (2004) 400-416.

[21] T.C. Matisziw, A.T. Murray, T.H. Grubesic, (2007) Bounding network interdiction vulnerability through cutest identification, in: A.T. Murray, T.H. Grubesic (Eds.), Critical infrastructure – reliability and vulnerability, Springer, Berlin Heidelberg, 2007, pp. 243-255.

[22] A.T. Murray, T.C. Matisziw, T.H. Grubesic, Critical network infrastructure analysis: Interdiction and system flow, J. of Geogr. Syst. 9 (2007) 103-117.

[23] K. Nagel, C.L. Barrett, Using microsimulation feedback for trip adaptation for realistic traffic in Dallas, Int. J. of Mod. Phys. C 8 (1997) 505-526.

[24] K. Nagel, M. Rickert, Parallel implementation of the TRANSIMS micro-simulation, Parallel Comput. 27 (2001) 1611-1639.

[25] ÖBB Netz- und Streckenentwicklung, Zugzahlen/Kapazität 2006, Technical report, ÖBB-Infrastruktur Betrieb AG, Wien, 2006.

[26] OECD, Road transport research: Outlook 2000, OECD, Paris, 1997.

[27] R Development Core Team, R: A language and environment for statistical computing, R Foundation for Statistical Computing, Wien, 2009.

[28] D.M. Scott, D.C. Novak, L. Aultman-Hall, F. Guo, Network robustness index: A new method for identifying critical links and evaluating the performance of transportation networks, J. of Transp. Geogr. 14 (2006) 215-227.

[29] J. Sullivan, L. Aultman-Hall, D.C. Novak, D. Scott, A review of current practice in network disruption analysis and an assessment of the ability to account for isolating links in transportation networks, Trans. Lett.: The Intern. J. of Transp. Res., 1 (2009) 271–280.

[30] J.L. Sullivan, D.C. Novak, L. Aultman-Hall, D.M. Scott, Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach, Transp. Res. Part A: Policy and Pract. 44 (2010) 323-336.

[31] M.A.P. Taylor, G.M. D'Este, Transport network vulnerability: A model for diagnosis of critical locations in transport infrastructure systems, in: A.T. Murray, T.H. Grubesic (Eds.), Critical infrastructure: Reliability and vulnerability, Springer, Heidelberg, 2007, pp. 9-30.

[32] S.V. Ukkusuri, W.F. Yushimito, A methodology to assess the criticality of highway transportation networks, J. of Transp. Secur., 2 (2009) 29-46.

[33] Via donau, Danube Navigation in Austria - Annual report 2009, Technical report, via donau, Wien, 2010.

[34] P. Vorsha, E. Petersen, R. Donnelly, Microsimulation in travel demand modeling: Lessons learned from the New York best practice model, Transp. Res. Rec. 1805 (2002) 68-77.

[35] W. Wang, W. Zang, X. Zang, Traffic micro-simulation of urban road network, in: Proc. Of the 1st Intern. Conf. on Transp. Inf. and Soc. (ICTIS), Wuhan, China, 2011.

Figures

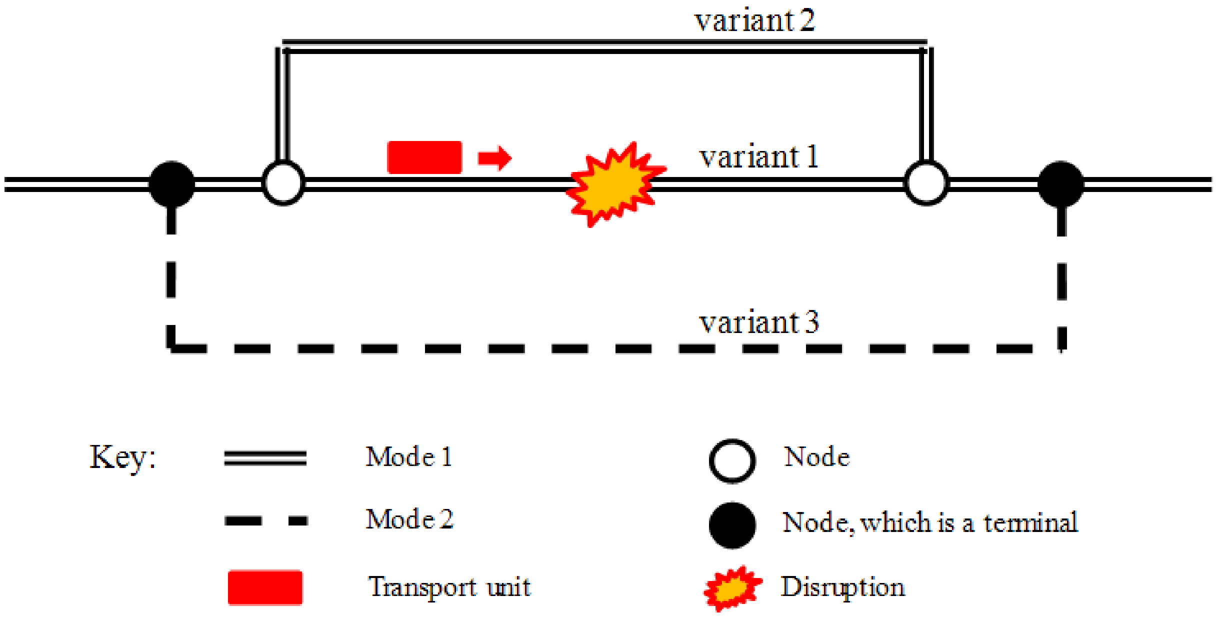

Figure 1: *A transport unit's possible choices in case of a disruption*

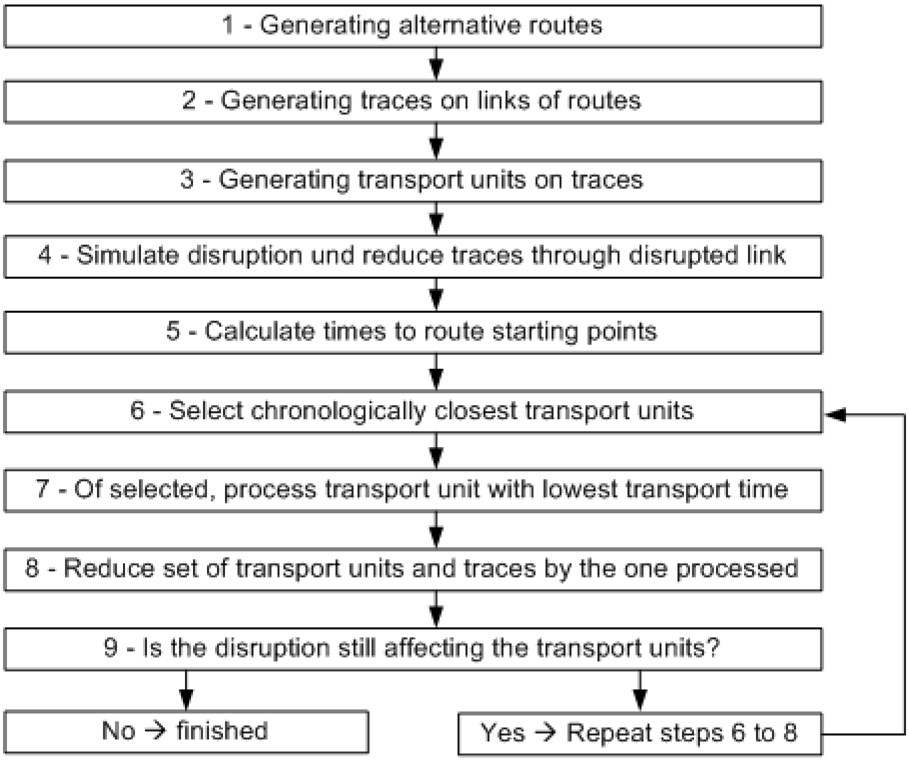

Figure 2: *The detailed operation of the model*

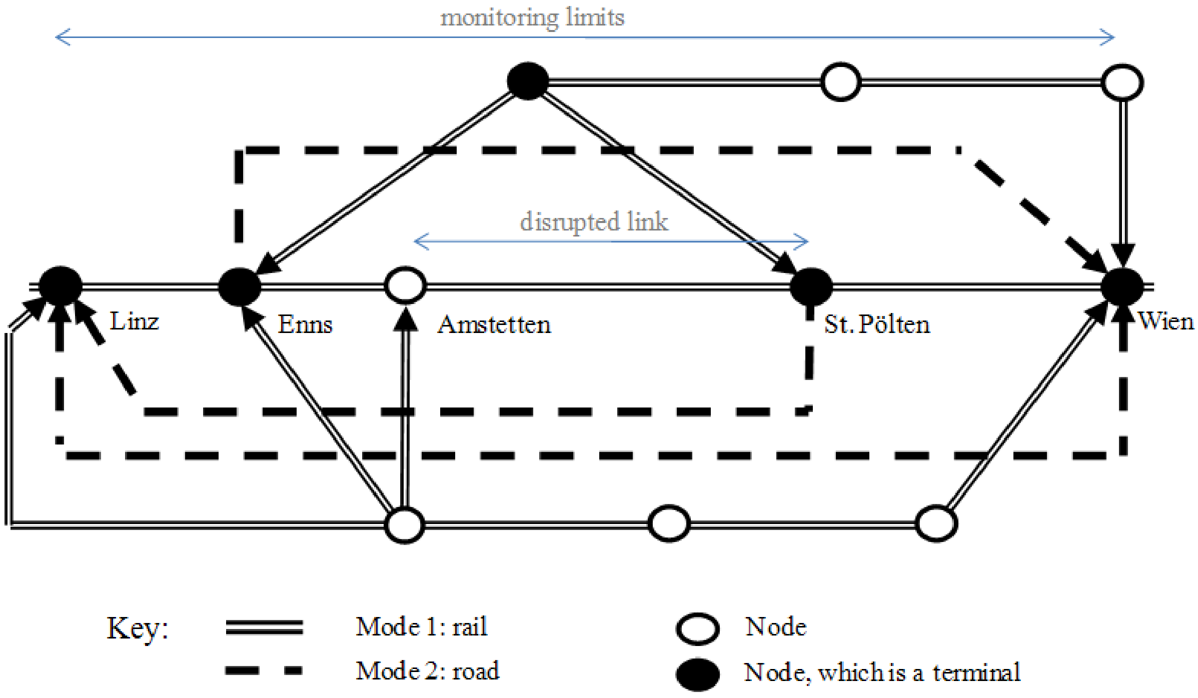

Figure 3: *A relevant link and its monitoring limits*

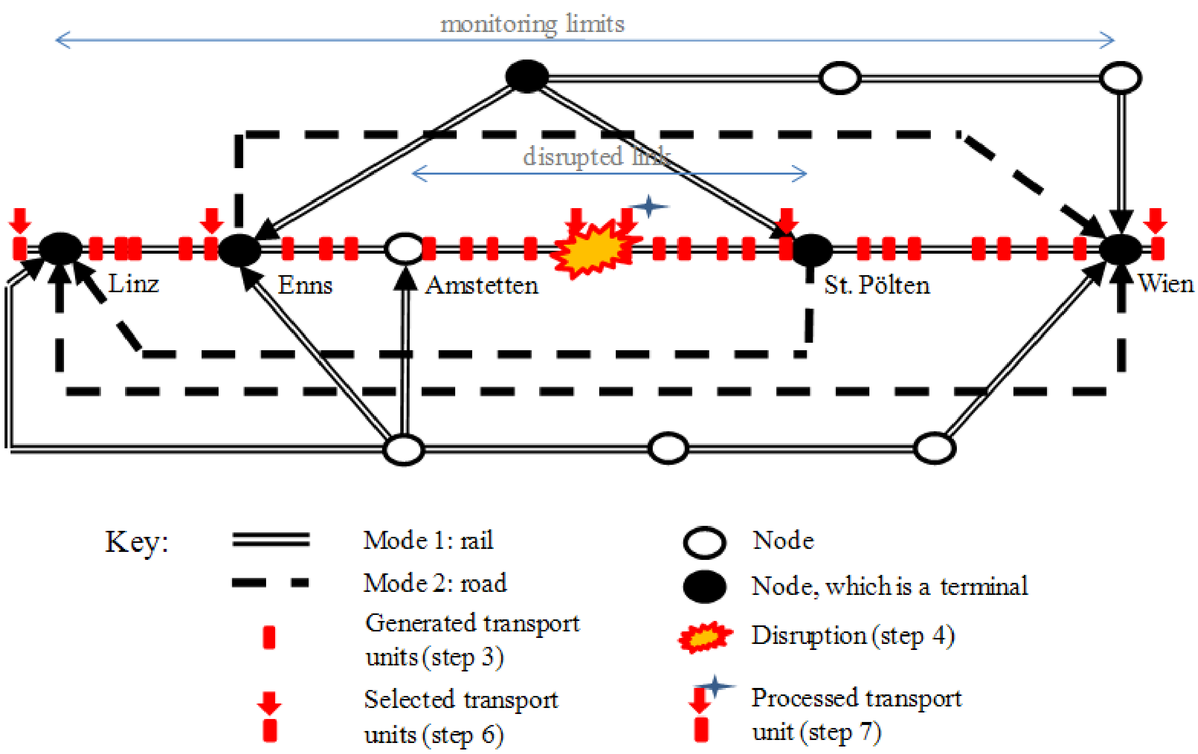

Figure 4: *Selecting the next processed transport unit*

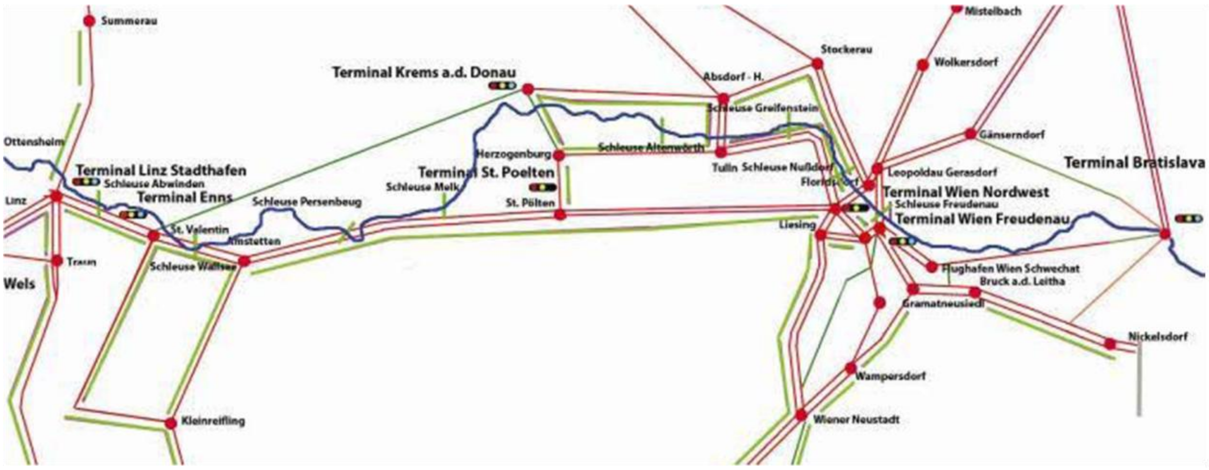

Figure 5: *The North Eastern area of the Austrian intermodal transport network*

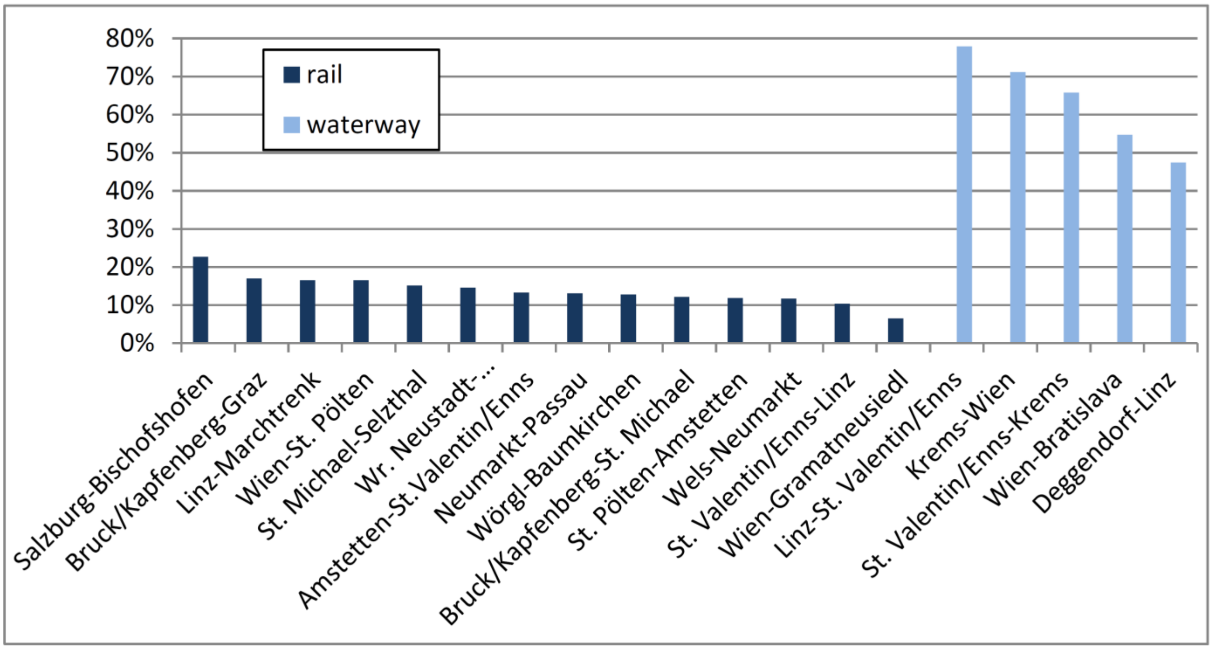

Figure 6: *The percentage of transport units, for every relevant link, choosing an alternative route in case of a disruption.*

Tables

time of day [hh:mm]	duration of the disruption [h]	capacity reduction [%]
08:00	2	50%
		100%
	6	50%
		100%
	24	50%
		100%
16:00	2	50%
		100%
	6	50%
		100%
	24	50%
		100%
24:00	2	50%
		100%
	6	50%
		100%
	24	50%
		100%

Table 1: *An overview of the applied disruption parameters*

Relevant link	TDDT [hh:mm:ss]	Rank	Affected units	Rank	Influence distance [km]	Rank	Influence duration [hh:mm:ss]	Rank	ADDT [hh:mm:ss]	Rank
St. Valentin/Enns-Linz	377:05:01	1	229.8	3	854.4	4	16:50:43	4	01:38:27	4
Linz-Marchtrenk	373:17:19	2	270.5	2	849.6	5	17:04:06	3	01:22:48	8
Wien-Gramatneusiedl	329:59:19	3	227.9	4	754.8	11	15:22:11	11	01:26:53	6
Bruck/Kapfenberg-St. Michael	296:25:59	4	186.2	7	763.4	10	15:28:54	10	01:35:31	5
St. Pölten-Amstetten	284:34:07	5	199.3	5	709.8	13	14:24:47	14	01:25:40	7
Wels-Neumarkt	251:46:42	6	132.7	11	786.1	9	16:12:50	8	01:53:52	2
Wörgl-Baumkirchen	237:11:30	7	191.1	6	876.7	2	16:49:38	5	01:14:29	9
Neumarkt-Passau	233:49:06	8	106.8	13	735.6	12	15:16:23	12	02:11:20	1
Wien-St. Pölten	218:28:53	9	298.7	1	1072.7	1	21:09:25	1	00:43:53	14
Amstetten-St.Valentin/Enns	212:26:28	10	184.1	8	688.1	14	14:29:43	13	01:09:14	10
Wr. Neustadt-Bruck/Kapfenberg	169:02:04	11	162.7	9	818.2	6	16:25:15	6	01:02:21	12
St. Michael-Selzthal	159:06:43	12	85.4	14	799.9	7	16:20:50	7	01:51:46	3
Bruck/Kapfenberg-Graz	131:44:59	13	121.4	12	873.5	3	17:17:15	2	01:05:08	11
Salzburg-Bischofshofen	116:04:11	14	158.1	10	794.5	8	15:53:40	9	00:44:02	13

Table 2: *The, over all scenarios averaged, NPI's for the relevant rail links, ranked by the TDDT*

Disruption	TDDT	Affected units	Infl. distance	Infl. duration	ADDT
2h; 50%	0.64	0.43	0.26	0.19	0.25
2h; 100%	1.00	0.67	0.35	0.40	0.78
6h; 50%	1.00	0.49	0.29	0.23	0.69
6h; 100%	1.00	0.46	0.35	0.26	1.00
24h; 50%	1.00	0.77	0.48	0.42	0.75
24h; 100%	0.95	0.76	0.83	0.77	0.63
OVERALL	**1.00**	**0.68**	**0.43**	**0.36**	**0.63**

Table 3: *The NPI's of the link St. Valentin/Enns ⇆ Linz for different scenarios relative to the other relevant links*

Disruption	TDDT	Affected units	Infl. distance	Infl. duration	ADDT
2h; 50%	1.00	1.00	1.00	1.00	1.00
2h; 100%	0.80	1.00	1.00	1.00	0.88
6h; 50%	0.91	1.00	1.00	1.00	1.00
6h; 100%	0.73	1.00	1.00	1.00	0.03
24h; 50%	0.61	1.00	1.00	1.00	0.50
24h; 100%	0.28	0.85	0.99	0.96	0.00
OVERALL	**0.39**	**1.00**	**1.00**	**1.00**	**0.00**

Table 4: *The NPI's of the link Wien ⇆ St. Pölten for different scenarios relative to the other relevant links*